

ONLINE OUTPUT MULTIPLEXER FILTER MEASUREMENT

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit under 35 U.S.C. §119(e) of the following U.S. Provisional Patent Application, which is incorporated by reference herein:

[0002] Application Serial No. 60/421,290, filed October 25, 2002, by Ernest C. Chen, entitled "On-Line OMUX Filter Measurement," attorneys' docket number PD-201150 (109.93-US-P1).

[0003] This is a continuation-in-part application and claims the benefit under 35 U.S.C. §120 of the following co-pending and commonly-assigned U.S. utility patent application, which is incorporated by reference herein:

[0004] Utility Application Serial No. 09/844,401, filed April 27, 2001, by Ernest C. Chen, entitled "LAYERED MODULATION FOR DIGITAL SIGNALS," attorneys' docket number PD-200181 (109.0051-US-01).

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0005] The present invention relates to systems and methods for measuring (on-line) an output multiplexor filter transfer function.

2. Description of the Related Art

[0006] Digital signal communication systems have been used in various fields, including digital TV signal transmission, either terrestrial or satellite. As the various digital signal

communication systems and services evolve, there is a burgeoning demand for increased data throughput and added services. However, it is more difficult to implement either improvement in old systems and new services when it is necessary to replace existing legacy hardware, such as transmitters and receivers. New systems and services are advantaged when they can utilize existing legacy hardware. In the realm of wireless communications, this principle is further highlighted by the limited availability of electromagnetic spectrum. Thus, it is not possible (or at least not practical) to merely transmit enhanced or additional data at a new frequency.

[0007] The conventional method of increasing spectral capacity is to move to a higher-order modulation, such as from quadrature phase shift keying (QPSK) to eight phase shift keying (8PSK) or sixteen quadrature amplitude modulation (16QAM). Unfortunately, QPSK receivers cannot demodulate conventional 8PSK or 16QAM signals. As a result, legacy customers with QPSK receivers must upgrade their receivers in order to continue to receive any signals transmitted with an 8PSK or 16QAM modulation.

[0008] It is advantageous for systems and methods of transmitting signals to accommodate enhanced and increased data throughput without requiring additional frequency. In addition, it is advantageous for enhanced and increased throughput signals for new receivers to be backwards compatible with legacy receivers. There is further an advantage for systems and methods which allow transmission signals to be upgraded from a source separate from the legacy transmitter.

[0009] It has been proposed that a layered modulation signal, transmitting non-coherently both upper and lower layer signals, can be employed to meet these needs. See Utility Application Serial No. 09/844,401. Such layered modulation systems allow higher information throughput with backwards compatibility. However, even when backward compatibility is not required (such as with an entirely new system), layered modulation can

still be advantageous because it requires a travelling wave tube amplifier (TWTA) peak power significantly lower than that for a conventional 8PSK or 16QAM modulation format for a given throughput.

[0010] In addition to the above, an input multiplexor (IMUX) and output multiplexor (OMUX) may be commonly used in a satellite when processing the signals. In this regard, various satellite receivers receive the broadband uplink signal. A separate receiver is used to tune/demodulate each frequency channel from the broadband uplink signal. The demodulated/individual channels pass through the IMUX that is used to separate and filter (out noise from) the individual channels. The various channels/frequencies are then amplified in and distributed by the TWTA (or power amplifiers(s)). The amplified signal passes through the OMUX which combines the power signals coming from the TWTA and feeds the combined signal to the transmit antenna for transmission via downlink signal back to earth. The OMUX (or an OMUX filter transfer function) may also provide channel filtering and/or harmonic filtering (e.g., to absorb and reject TWTA harmonics).

[0011] For various reasons, it may be desirable to determine and evaluate the various satellite processing modules (e.g., the IMUX, the TWTA, and the OMUX) (e.g., as part of routine satellite payload system monitoring). In the prior art, such an analysis was merely conducted by comparing the uplink signal to the downlink signal. However, such a comparison fails to determine the impact of individual satellite processing modules. Further, such a comparison may not provide an accurate representation of the functions performed by the satellite processing modules. To provide a high-fidelity signal (e.g., at/by the receiver), it is desirable to accurately determine such satellite processing module functionality.

SUMMARY OF THE INVENTION

[0012] One or more embodiments of the invention provide a method and system for detecting and measuring output multiplexor (OMUX) filter transfer functions of magnitude/phase versus frequency. The OMUX filter is often used in a satellite system to combine power signals and provide a downlink signal from the satellite. The received downlink signal is demodulated and then remodulated to estimate the OMUX filter input signal. The received downlink signal is then compared to the estimated OMUX filter input signal to provide the transfer function. The technique includes an examination of bandwidth, flatness, and group delay. Further, the determined transfer function may be used in layered modulation (e.g., in signal cancellation) and/or may also be incorporated into a routine satellite payload system check/monitoring.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

[0014] FIG. 1 is a diagram illustrating an overview of a single satellite video distribution system;

[0015] FIG. 2 is a block diagram showing a typical uplink configuration for a single satellite transponder;

[0016] FIG. 3A is a diagram of a representative data stream;

[0017] FIG. 3B is a diagram of a representative data packet;

[0018] FIG. 4 is a block diagram showing one embodiment of the modulator for the uplink signal;

[0019] FIG. 5 is a block diagram of an integrated receiver/decoder (IRD);

[0020] FIGS. 6A - 6C are diagrams illustrating the basic relationship of signal layers in a layered modulation transmission;

[0021] FIGS. 7A - 7C are diagrams illustrating a signal constellation of a second transmission layer over the first transmission layer after first layer demodulation;

[0022] FIG. 8A is a diagram showing a system for transmitting and receiving layered modulation signals;

[0023] FIG. 8B is a diagram showing an exemplary satellite transponder for receiving and transmitting layered modulation signals;

[0024] FIG. 9 is a block diagram depicting one embodiment of an enhanced IRD capable of receiving layered modulation signals;

[0025] FIG. 10A is a block diagram of one embodiment of the enhanced tuner/modulator and FEC encoder;

[0026] FIG. 10B depicts another embodiment of the enhanced tuner/modulator wherein layer subtraction is performed on the received layered signal;

[0027] FIGS. 11A and 11B depict the relative power levels of example embodiments of the present invention;

[0028] FIG. 12 illustrates an exemplary computer system that could be used to implement selected modules or functions the present invention;

[0029] FIG. 13 is a graph of the phase and magnitude to frequency for an example OMUX filter transfer function used for simulations in accordance with one or more embodiments of the invention;

[0030] FIG. 14 illustrates the processing of FIG. 8B followed by the on-line measurement of the OMUX filter transfer function in accordance with one or more embodiments of the invention;

[0031] FIG. 15A illustrates the simulated/estimated signal spectrum $F_I'(f)$ without the OMUX filter;

[0032] FIG. 15B illustrates the simulated/estimated signal spectrum $F_O'(f)$ with the OMUX filter;

[0033] FIG. 16 illustrates the estimated OMUX transfer function in accordance with one or more embodiments of the invention; and

[0034] FIG. 17 is a flow chart illustrating the process for measuring the OMUX transfer function in accordance with one or more embodiments of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0035] In the following description of the preferred embodiment, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration a specific embodiment in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

1. Video Distribution System

[0036] FIG. 1 is a diagram illustrating an overview of a single satellite video distribution system 100. The video distribution system 100 comprises a control center 102 in communication with an uplink center 104 via a ground or other link 114 and with a subscriber receiver station 110 via a public switched telephone network (PSTN) or other link 120. The control center 102 provides program material (e.g. video programs, audio programs and data) to the uplink center 104 and coordinates with the subscriber receiver stations 110 to offer, for example, pay-per-view (PPV) program services, including billing and associated decryption of video programs.

[0037] The uplink center 104 receives program material and program control information from the control center 102, and using an uplink antenna 106 and transmitter 105, transmits the program material and program control information to the satellite 108 via uplink signal 116. The satellite receives and processes this information, and transmits the video programs and control information to the subscriber receiver station 110 via downlink signal 118 using transmitter 107. The subscriber receiving station 110 receives this information using the outdoor unit (ODU) 112, which includes a subscriber antenna and a low noise block converter (LNB).

[0038] In one embodiment, the subscriber receiving station antenna is an 18-inch slightly oval-shaped Ku-band antenna. The slight oval shape is due to the 22.5 degree offset feed of the LNB (low noise block converter) which is used to receive signals reflected from the subscriber antenna. The offset feed positions the LNB out of the way so it does not block any surface area of the antenna minimizing attenuation of the incoming microwave signal.

[0039] The video distribution system 100 can comprise a plurality of satellites 108 in order to provide wider terrestrial coverage, to provide additional channels, or to provide additional bandwidth per channel. In one embodiment of the invention, each satellite comprises 16

transponders to receive and transmit program material and other control data from the uplink center 104 and provide it to the subscriber receiving stations 110. Using data compression and multiplexing techniques the channel capabilities, two satellites 108 working together can receive and broadcast over 150 conventional (non-HDTV) audio and video channels via 32 transponders.

[0040] While the invention disclosed herein will be described with reference to a satellite-based video distribution system 100, the present invention may also be practiced with terrestrial-based transmission of program information, whether by broadcasting means, cable, or other means. Further, the different functions collectively allocated among the control center 102 and the uplink center 104 as described above can be reallocated as desired without departing from the intended scope of the present invention.

[0041] Although the foregoing has been described with respect to an embodiment in which the program material delivered to the subscriber 122 is video (and audio) program material such as a movie, the foregoing method can be used to deliver program material comprising purely audio information or other data as well.

2.1 Uplink Configuration

[0042] FIG. 2 is a block diagram showing a typical uplink configuration for a single satellite 108 transponder, showing how video program material is uplinked to the satellite 108 by the control center 102 and the uplink center 104. FIG. 2 shows three video channels (which may be augmented respectively with one or more audio channels for high fidelity music, soundtrack information, or a secondary audio program for transmitting foreign languages), a data channel from a program guide subsystem 206 and computer data information from a computer data source 208.

[0043] Typical video channels are provided by a program source 200A-200C of video material (collectively referred to hereinafter as program source(s) 200). The data from each program source 200 is provided to an encoder 202A-202C (collectively referred to hereinafter as encoder(s) 202). Each of the encoders accepts a program time stamp (PTS) from the controller 216. The PTS is a wrap-around binary time stamp that is used to assure that the video information is properly synchronized with the audio information after encoding and decoding. A PTS time stamp is sent with each I-frame of the MPEG encoded data.

[0044] In one embodiment of the present invention, each encoder 202 is a second generation Motion Picture Experts Group (MPEG-2) encoder, but other decoders implementing other coding techniques can be used as well. The data channel can be subjected to a similar compression scheme by an encoder (not shown), but such compression is usually either unnecessary, or performed by computer programs in the computer data source (for example, photographic data is typically compressed into *.TIF files or *.JPG files before transmission). After encoding by the encoders 202, the signals are converted into data packets by a packetizer 204A-204F (collectively referred to hereinafter as packetizer(s) 204) associated with each program source 200.

[0045] The output data packets are assembled using a reference from the system clock 214 (SCR), and from the conditional access manager 210, which provides the service channel identifier (SCID) to the packetizers 204 for use in generating the data packets. These data packets are then multiplexed into serial data and transmitted.

2.2 Broadcast Data Stream Format and Protocol

[0046] FIG. 3A is a diagram of a representative data stream. The first packet 302 comprises information from video channel 1 (data coming from, for example, the first video program source 200A). The next packet 304 comprises computer data information that was obtained, for example from the computer data source 208. The next packet 306 comprises information from video channel 5 (from one of the video program sources 200). The next packet 308 comprises program guide information such as the information provided by the program guide subsystem 206. As shown in FIG. 3A, null packets 310 created by the null packet module 212 may be inserted into the data stream as desired followed by further data packets 312, 314, 316 from the program sources 200.

[0047] Referring back to FIG. 2, the data stream therefore comprises a series of packets (302-316) from any one of the data sources (e.g. program sources 200, program guide subsystem 206, computer data source 208) in an order determined by the controller 216. The data stream is encrypted by the encryption module 218, modulated by the modulator 220 (typically using a QPSK modulation scheme), and provided to the transmitter 105, which broadcasts the modulated data stream on a frequency bandwidth to the satellite via the antenna 106. The receiver 500 at the receiver station 110 receives these signals, and using the SCID, reassembles the packets to regenerate the program material for each of the channels.

[0048] FIG. 3B is a diagram of a data packet. Each data packet (e.g. 302-316) is 147 bytes long, and comprises a number of packet segments. The first packet segment 320 comprises two bytes of information containing the SCID and flags. The SCID is a unique 12-bit number that uniquely identifies the data packet's data channel. The flags include 4 bits that are used to control other features. The second packet segment 322 is made up of a 4-bit packet type indicator and a 4-bit continuity counter. The packet type generally identifies the packet as

one of the four data types (video, audio, data, or null). When combined with the SCID, the packet type determines how the data packet will be used. The continuity counter increments once for each packet type and SCID. The next packet segment 324 comprises 127 bytes of payload data, which in the cases of packets 302 or 306 is a portion of the video program provided by the video program source 200. The final packet segment 326 is data required to perform forward error correction.

[0049] FIG. 4 is a block diagram showing one embodiment of the modulator 220. The modulator 220 optionally comprises a forward error correction (FEC) encoder 404 which accepts the first signal symbols 402 and adds redundant information that are used to reduce transmission errors. The coded symbols 405 are modulated by modulator 406 according to a first carrier 408 to produce an upper layer modulated signal 410. Second symbols 420 are likewise provided to an optional second FEC encoder 422 to produce coded second symbols 424. The coded second symbols 424 are provided to a second modulator 414, which modulates the coded second symbols 424 according to a second carrier 416 to produce a lower layer modulated signal 418. The upper layer modulated signal 410 and the lower layer modulated signal 418 are therefore uncorrelated. Thus, the upper layer signal 410 and the lower layer signal 418 can be transmitted to separate transponders on one or more satellites 108 via separate uplink signals 116. Thus, the lower layer signal 418 can be implemented from a separate satellite 108 that receives a separate uplink signal 116. However, in the downlink signal 118 the upper layer signal 410, must be a sufficiently greater amplitude signal than the lower layer signal 418, to maintain the signal constellations shown in FIG. 6 and FIG. 7.

[0050] It should be noted that it may be more efficient to retrofit an existing system by using a transponder on a separate satellite 108 to transmit the lower layer downlink signal over the existing legacy downlink signal rather than replacing the legacy satellite with one

that will transmit both downlink signal layers. Emphasis can be given to accommodating the downlink legacy signal in implementing a layered downlink broadcast.

2.3 Integrated Receiver/Decoder

[0051] FIG. 5 is a block diagram of an integrated receiver/decoder (IRD) 500 (also hereinafter alternatively referred to as receiver 500). The receiver 500 comprises a tuner/demodulator 504 communicatively coupled to an ODU 112 having one or more low noise blocks (LNBs) 502. The LNB 502 converts the 12.2- to 12.7 GHz downlink 118 signal from the satellites 108 to, e.g., a 950-1450 MHz signal required by the IRD's 500 tuner/demodulator 504. Typically, the LNB 502 may provide either a dual or a single output. The single-output LNB 502 has only one RF connector, while the dual output LNB 502 has two RF output connectors and can be used to feed a second tuner 504, a second receiver 500, or some other form of distribution system.

[0052] The tuner/demodulator 504 isolates a single, digitally modulated 24 MHz transponder signal, and converts the modulated data to a digital data stream. The digital data stream is then supplied to a forward error correction (FEC) decoder 506. This allows the IRD 500 to reassemble the data transmitted by the uplink center 104 (which applied the forward error correction to the desired signal before transmission to the subscriber receiving station 110) verifying that the correct data signal was received, and correcting errors, if any. The error-corrected data may be fed from the FEC decoder module 506 to the transport module 508 via an 8-bit parallel interface.

[0053] The transport module 508 performs many of the data processing functions performed by the IRD 500. The transport module 508 processes data received from the FEC decoder module 506 and provides the processed data to the video MPEG decoder 514 and

the audio MPEG decoder 517. As needed the transport module employs system RAM 528 to process the data. In one embodiment of the present invention, the transport module 508, video MPEG decoder 514 and audio MPEG decoder 517 are all implemented on integrated circuits. This design promotes both space and power efficiency, and increases the security of the functions performed within the transport module 508. The transport module 508 also provides a passage for communications between the microcontroller 510 and the video and audio MPEG decoders 514, 517. As set forth more fully hereinafter, the transport module also works with the conditional access module (CAM) 512 to determine whether the receiver 500 is permitted to access certain program material. Data from the transport module 508 can also be supplied to external communication module 526.

[0054] The CAM 512 functions in association with other elements to decode an encrypted signal from the transport module 508. The CAM 512 may also be used for tracking and billing these services. In one embodiment of the present invention, the CAM 512 is a removable smart card, having contacts cooperatively interacting with contacts in the IRD 500 to pass information. In order to implement the processing performed in the CAM 512, the IRD 500, and specifically the transport module 508 provides a clock signal to the CAM 512.

[0055] Video data is processed by the MPEG video decoder 514. Using the video random access memory (RAM) 536, the MPEG video decoder 514 decodes the compressed video data and sends it to an encoder or video processor 516, which converts the digital video information received from the video MPEG module 514 into an output signal usable by a display or other output device. By way of example, processor 516 may comprise a National TV Standards Committee (NTSC) or Advanced Television Systems Committee (ATSC) encoder. In one embodiment of the invention both S-Video and ordinary video (NTSC or ATSC) signals are provided. Other outputs may also be utilized, and are advantageous if high definition programming is processed.

[0056] Audio data is likewise decoded by the MPEG audio decoder 517. The decoded audio data may then be sent to a digital to analog (D/A) converter 518. In one embodiment of the present invention, the D/A converter 518 is a dual D/A converter, one for the right and left channels. If desired, additional channels can be added for use in surround sound processing or secondary audio programs (SAPs). In one embodiment of the invention, the dual D/A converter 518 itself separates the left and right channel information, as well as any additional channel information. Other audio formats may similarly be supported. For example, other audio formats such as multi-channel DOLBY DIGITAL AC-3 may be supported.

[0057] A description of the processes performed in the encoding and decoding of video streams, particularly with respect to MPEG and JPEG encoding/decoding, can be found in Chapter 8 of "Digital Television Fundamentals," by Michael Robin and Michel Poulin, McGraw-Hill, 1998, which is hereby incorporated by reference herein.

[0058] The microcontroller 510 receives and processes command signals from a remote control, an IRD 500 keyboard interface, and/or other suitable input device 524. The microcontroller 510 receives commands for performing its operations from a processor programming memory, which permanently stores such instructions for performing such commands. The processor programming memory may comprise a read only memory (ROM) 538, an electrically erasable programmable read only memory (EEPROM) 522 or, similar memory device. The microcontroller 510 also controls the other digital devices of the IRD 500 via address and data lines (denoted "A" and "D" respectively, in FIG. 5).

[0059] The modem 540 connects to the customer's phone line via the PSTN port 120. It calls, e.g. the program provider, and transmits the customer's purchase information for billing purposes, and/or other information. The modem 540 is controlled by the microprocessor

510. The modem 540 can output data to other I/O port types including standard parallel and serial computer I/O ports.

[0060] The present invention also comprises a local storage unit such as the video storage device 532 for storing video and/or audio data obtained from the transport module 508. Video storage device 532 can be a hard disk drive, a read/writable compact disc of DVD, a solid state RAM, or any other suitable storage medium. In one embodiment of the present invention, the video storage device 532 is a hard disk drive with specialized parallel read/write capability so that data may be read from the video storage device 532 and written to the device 532 at the same time. To accomplish this feat, additional buffer memory accessible by the video storage 532 or its controller may be used. Optionally, a video storage processor 530 can be used to manage the storage and retrieval of the video data from the video storage device 532. The video storage processor 530 may also comprise memory for buffering data passing into and out of the video storage device 532. Alternatively or in combination with the foregoing, a plurality of video storage devices 532 can be used. Also alternatively or in combination with the foregoing, the microcontroller 510 can also perform the operations required to store and or retrieve video and other data in the video storage device 532.

[0061] The video processing module 516 input can be directly supplied as a video output to a viewing device such as a video or computer monitor. In addition, the video and/or audio outputs can be supplied to an RF modulator 534 to produce an RF output and/or 8 vestigial side band (VSB) suitable as an input signal to a conventional television tuner. This allows the receiver 500 to operate with televisions without a video output.

[0062] Each of the satellites 108 comprises a transponder, which accepts program information from the uplink center 104, and relays this information to the subscriber receiving station 110. Known multiplexing techniques are used so that multiple channels can

be provided to the user. These multiplexing techniques include, by way of example, various statistical or other time domain multiplexing techniques and polarization multiplexing. In one embodiment of the invention, a single transponder operating at a single frequency band carries a plurality of channels identified by respective service channel identification (SCID).

[0063] Preferably, the IRD 500 also receives and stores a program guide in a memory available to the microcontroller 510. Typically, the program guide is received in one or more data packets in the data stream from the satellite 108. The program guide can be accessed and searched by the execution of suitable operation steps implemented by the microcontroller 510 and stored in the processor ROM 538. The program guide may include data to map viewer channel numbers to satellite transponders and service channel identifications (SCIDs), and also provide TV program listing information to the subscriber 122 identifying program events.

[0064] The functionality implemented in the IRD 500 depicted in FIG. 5 can be implemented by one or more hardware modules, one or more software modules defining instructions performed by a processor, or a combination of both.

[0065] The present invention provides for the modulation of signals at different power levels and advantageously for the signals to be non-coherent from each layer. In addition, independent modulation and coding of the signals may be performed. Backwards compatibility with legacy receivers, such as a quadrature phase shift keying (QPSK) receiver is enabled and new services are provided to new receivers. A typical new receiver of the present invention uses two demodulators and one recoder/remodulator as will be described in detail hereafter.

[0066] In a typical backwards-compatible embodiment of the present invention, the legacy QPSK signal is boosted in power to a higher transmission (and reception) level. This creates a power "room" in which a new lower layer signal may operate. The legacy receiver will not

be able to distinguish the new lower layer signal, from additive white Gaussian noise, and thus operates in the usual manner. The optimum selection of the layer power levels is based on accommodating the legacy equipment, as well as the desired new throughput and services.

[0067] The new lower layer signal is provided with a sufficient carrier to thermal noise ratio to function properly. The new lower layer signal and the boosted legacy signal are non-coherent with respect to each other. Therefore, the new lower layer signal can be implemented from a different TWTA and even from a different satellite. The new lower layer signal format is also independent of the legacy format, e.g., it may be QPSK or 8PSK, using the conventional concatenated FEC code or using a new Turbo code. The lower layer signal may even be an analog signal.

[0068] The combined layered signal is demodulated and decoded by first demodulating the upper layer to remove the upper carrier. The stabilized layered signal may then have the upper layer FEC decoded and the output upper layer symbols communicated to the upper layer transport. The upper layer symbols are also employed in a recoder/remodulator, to generate an idealized upper layer signal. The idealized upper layer signal is then subtracted from the stable layered signal to reveal the lower layer signal. The lower layer signal is then demodulated and FEC decoded and communicated to the lower layer transport.

[0069] Signals, systems and methods using the present invention may be used to supplement a pre-existing transmission compatible with legacy receiving hardware in a backwards-compatible application or as part of a preplanned layered modulation architecture providing one or more additional layers at a present or at a later date.

2.4 Layered Signals

[0070] FIGS. 6A - 6C illustrate the basic relationship of signal layers in a received layered modulation transmission. FIG. 6A illustrates an upper layer signal constellation 600 of a transmission signal showing the signal points or symbols 602. FIG. 6B illustrates the lower layer signal constellation of symbols 604 over the upper layer signal constellation 600 where the layers are coherent (or synchronized). FIG. 6C illustrates a lower layer signal 606 of a second transmission layer over the upper layer constellation where the layers are non-coherent. The lower layer 606 rotates about the upper layer constellation 602 due to the relative modulating frequencies of the two layers in a non-coherent transmission. Both the upper and lower layers rotate about the origin due to the first layer modulation frequency as described by path 608.

[0071] FIGS. 7A - 7C are diagrams illustrating a non-coherent relationship between a lower transmission layer over the upper transmission layer after upper layer demodulation. FIG. 7A shows the constellation 700 before the first carrier recovery loop (CRL) of the upper layer and The constellation rings 702 rotate around the large radius circle indicated by the dashed line. FIG. 7B shows the constellation 704 after CRL of the upper layer where the rotation of the constellation rings 702 is stopped. The constellation rings 702 are the signal points of the lower layer around the nodes 602 of the upper layer. FIG. 7C depicts a phase distribution of the received signal with respect to nodes 602.

[0072] Relative modulating frequencies of the non-coherent upper and lower layer signals cause the lower layer constellation to rotate around the nodes 602 of the upper layer constellation to form rings 702. After the lower layer CRL this rotation is eliminated and the nodes of the lower layer are revealed (as shown in FIG. 6B). The radius of the lower layer constellation rings 702 is indicative of the lower layer power level. The thickness of the rings 702 is indicative of the carrier to noise ratio (CNR) of the lower layer. As the two

layers are non-coherent, the lower layer may be used to transmit distinct digital or analog signals.

[0073] FIG. 8A is a diagram showing a system for transmitting and receiving layered modulation signals. Separate transmitters 107A, 107B (which include TWTAs to amplify the signals), as may be located on any suitable platform, such as satellites 108A, 108B, are used to non-coherently transmit different layers of a signal of the present invention. Uplink signals 116 are typically transmitted to each satellite 108A, 108B from one or more uplink centers 104 with one or more transmitters 105 via an antenna 106.

[0074] FIG. 8B is a diagram illustrating an exemplary satellite transponder 107 for receiving and transmitting layered modulation signals on a satellite 108. The uplink signal represented in frequency domain $F_U(f)$ 116 is received by the satellite 108 (e.g., by multiple satellite receivers). Each satellite receiver is tuned to a channel frequency (in the uplink signal $F_U(f)$) using the input multiplexor (IMUX) 814. The IMUX 814 (also referred to as an IMUX filter) filters out adjacent-channel signals and noise and focuses each receiver on the channel of interest. Following processing by the IMUX 814, the signal is amplified with a traveling wave tube amplifier (TWT) 816. The amplified signal from the TWT 816 provides the input signal $F_I(f)$ for the output multiplexer (OMUX) (also referred to as OMUX filter) 818.

[0075] As described above, the amplified signal $F_I(f)$ passes through the OMUX which feeds the combined output signal $F_O(f)$ to the transmit antenna for transmission via downlink signal to the receivers 802, 500. The OMUX 818 may also provide channel filtering and/or harmonic filtering (e.g., to absorb and reject TWT harmonics). The processing performed by the OMUX 818 may be referred to as an OMUX filter transfer function. FIG. 13 is a graph of the phase and magnitude to frequency for an example OMUX filter transfer function in accordance with one or more embodiments of the invention. As illustrated, the OMUX

filter transfer function provides a fairly linear output phase and magnitude from about -12 MHz to 12 MHz centered around the carrier frequency.

[0076] The layered signals 808A, 808B (e.g. multiple downlink signals 118) are received at receiver antennas 812A, 812B, such as satellite dishes, each with a low noise block (LNB) 810A, 810B where they are then coupled to integrated receiver/decoders (IRDs) 500, 802. For example, first satellite 108A and transmitter 107A can transmit an upper layer legacy signal 808A and second satellite 108B and transmitter 107B can transmit a lower layer signal 808B. Although both signals 808A, 808B arrive at each antenna 812A, 812B and LNB 810A, 810B, only the layer modulation IRD 802 is capable of decoding both signals 808A, 808B. The legacy receiver 500 is only capable of decoding the upper layer legacy signal 808A; the lower layer signal 808B appears only as noise to the legacy receiver 500.

[0077] Because the signal layers can be transmitted non-coherently, separate transmission layers may be added at any time using different satellites 108A, 108B or other suitable platforms, such as ground-based or high altitude platforms. Thus, any composite signal, including new additional signal layers will be backwards compatible with legacy receivers 500, which will disregard the new signal layers. To ensure that the signals do not interfere, the combined signal and noise level for the lower layer must be at or below the allowed noise floor for the upper layer at the particular receiver antenna 812A, 812B.

[0078] Layered modulation applications include backwards compatible and non-backwards compatible applications. “Backwards compatible” in this sense, describes systems in which legacy receivers 500 are not rendered obsolete by the additional signal layer(s). Instead, even if the legacy receivers 500 are incapable of decoding the additional signal layer(s), they are capable of receiving the layered modulated signal and decoding the original signal layer. In these applications, the pre-existing system architecture is accommodated by the architecture of the additional signal layers. “Non-backwards compatible” describes a system

architecture which makes use of layered modulation, but the modulation scheme employed is such that pre-existing equipment is incapable of receiving and decoding the information on additional signal layer(s).

[0079] The pre-existing legacy IRDs 500 decode and make use of data only from the layer (or layers) they were designed to receive, unaffected by the additional layers. However, as will be described hereafter, the legacy signals may be modified to optimally implement the new layers. The present invention may be applied to existing direct satellite services which are broadcast to individual users in order to enable additional features and services with new receivers without adversely affecting legacy receivers and without requiring additional signal frequency.

2.5 Demodulator and Decoder

[0080] FIG. 9 is a block diagram depicting one embodiment of an enhanced IRD 802 capable of receiving layered modulation signals. The IRD includes many similar components as that of the legacy IRD 500 of FIG. 5. However, the enhanced IRD 802 includes a feedback path 902 in which the FEC decoded symbols are fed back to a enhanced modified tuner/demodulator 904 and transport module 908 for decoding both signal layers as detailed hereafter.

[0081] FIG. 10A is a block diagram of one embodiment of the enhanced tuner/modulator 904 and FEC encoder 506. FIG. 10A depicts reception where layer subtraction is performed on a signal where the upper layer carrier has already been demodulated. The upper layer of the received combined signal 1016 from the LNB 502, which may contain legacy modulation format, is provided to and processed by an upper layer demodulator 1004 to produce the stable demodulated signal 1020. The demodulated signal 1020 is communicatively coupled

to a FEC decoder 1002 which decodes the upper layer to produce the upper layer symbols which are output to an upper layer transport module 908. The upper layer symbols are also used to generate an idealized upper layer signal. The upper layer symbols may be produced from the decoder 1002 after Viterbi decode ($\text{BER} < 10^{-3}$ or so) or after Reed-Solomon (RS) decode ($\text{BER} < 10^{-9}$ or so), in typical decoding operations known to those skilled in the art. The upper layer symbols are provided via feedback path 902 from the upper layer decoder 1002 to a recoder/remodulator 1006 which effectively produces an idealized upper layer signal. The idealized upper level signal is subtracted from the demodulated upper layer signal 1020.

[0082] In order for the subtraction to yield a clean small lower layer signal, the upper layer signal must be precisely reproduced. The modulated signal may have been distorted, for example, by traveling wave tube amplifier (TWTA) 816 non-linearity or other non-linear or linear distortions in the transmission channel. The distortion effects are estimated from the received signal after the fact or from TWTA 816 characteristics which may be downloaded into the IRD in AM - AM and/or AM - PM maps 1018, used to eliminate the distortion. Further, the effects of the OMUX filter 818 may also be estimated and accounted for during signal reproduction.

[0083] A subtractor 1012 then subtracts the idealized upper layer signal from the stable demodulated signal 1020. This leaves the lower-power second layer signal. The subtractor 1012 may include a buffer or delay function to retain the stable demodulated signal 1020 while the idealized upper layer signal is being constructed. The second layer signal is demodulated by the lower level demodulator 1010 and FEC decoded by decoder 1008 according to its signal format to produce the lower layer symbols, which are provided to the transport module 908.

[0084] FIG. 10B depicts another embodiment wherein layer subtraction is performed on the received layered signal (prior to upper layer demodulation). In this case, the upper layer demodulator 1004 produces the upper carrier signal 1022 (as well as the stable demodulated signal output 1020). An upper carrier signal 1022 is provided to the recoder/remodulator 1006. The recoder/remodulator 1006 provides the recoded/remodulated signal to the non-linear distortion mapper 1018 which effectively produces an idealized upper layer signal. Unlike the embodiment shown in FIG. 10A, in this embodiment the idealized upper layer signal includes the upper layer carrier for subtraction from the received combined signal 808A, 808B.

[0085] Other equivalent methods of layer subtraction will occur to those skilled in the art and the present invention should not be limited to the examples provided here. Furthermore, those skilled in the art will understand that the present invention is not limited to two layers; additional layers may be included. Idealized upper layers are produced through recoding/remodulation from their respective layer symbols and subtracted. Subtraction may be performed on either the received combined signal or a demodulated signal. Finally, it is not necessary for all signal layers to be digital transmissions; the lowest layer may be an analog transmission.

[0086] The following analysis describes the exemplary two layer demodulation and decoding. It will be apparent to those skilled in the art that additional layers may be demodulated and decoded in a similar manner. The incoming combined signal is represented as:

$$s_{UL}(t) = f_U \left(M_U \exp(j\omega_U t + \theta_U) \sum_{m=-\infty}^{\infty} S_{Um} p(t - mT) \right) \\ + f_L \left(M_L \exp(j\omega_L t + \theta_L) \sum_{m=-\infty}^{\infty} S_{Lm} p(t - mT + \Delta T_m) \right) + n(t)$$

where, M_U is the magnitude of the upper layer QPSK signal and M_L is the magnitude of the lower layer QPSK signal and $M_L \ll M_U$. The signal frequencies and phase for the upper and lower layer signals are respectively ω_U, θ_U and ω_L, θ_L . The symbol timing misalignment between the upper and lower layers is ΔT_m . $p(t - mT)$ represents the time shifted version of the pulse shaping filter $p(t)$ 414 employed in signal modulation. QPSK symbols S_{Um} and S_{Lm} are elements of $\left\{ \exp(j \frac{n\pi}{2}), n = 0, 1, 2, 3 \right\}$. $f_U(\cdot)$ and $f_L(\cdot)$ denote the distortion function of the TWTAs for the respective signals.

[0087] Ignoring $f_U(\cdot)$ and $f_L(\cdot)$ and noise $n(t)$, the following represents the combined signal after removing the upper carrier:

$$s'_{UL}(t) = M_U \sum_{m=-\infty}^{\infty} S_{Um} p(t - mT) + M_L \exp\{j(\omega_L - \omega_U)t + \theta_L - \theta_U\} \sum_{m=-\infty}^{\infty} S_{Lm} p(t - mT + \Delta T_m)$$

Because of the magnitude difference between M_U and M_L , the upper layer demodulator 1004 and decoder 1002 disregard the M_L component of the $s'_{UL}(t)$.

[0088] After subtracting the upper layer from $s_{UL}(t)$ in the subtractor 1012, the following remains:

$$s_L(t) = M_L \exp\{j(\omega_L - \omega_U)t + \theta_L - \theta_U\} \sum_{m=-\infty}^{\infty} S_{Lm} p(t - mT + \Delta T_m)$$

Any distortion effects, such as TWTA nonlinearity effects are estimated for signal subtraction. In a typical embodiment of the present invention, the upper and lower layer frequencies are substantially equal. Significant improvements in system efficiency can be obtained by using a frequency offset between layers.

[0089] Using the present invention, two-layered backward compatible modulation with QPSK doubles a current 6/7 rate capacity by adding a TWTA approximately 6.2 dB above an existing TWTA power. New QPSK signals may be transmitted from a separate transmitter, from a different satellite for example. In addition, there is no need for linear travelling wave tube amplifiers (TWTAs) as with 16QAM. Also, no phase error penalty is imposed on higher order modulations as in 8PSK and 16QAM.

3.0 Power Levels of Modulation Layers

[0090] In a layered modulation system, the relationship between the individual modulation layers can be structured to facilitate backward compatible applications. Alternately, a new layer structure can be designed to optimize the combined efficiency and/or performance of the layered modulation system.

3.1 Backward Compatible Applications

[0091] The present invention may be used in Backward Compatible Applications. In such applications, a lower layer signal may take advantage of advanced forward error correction (FEC) coding techniques to lower the overall transmission power required by the system.

[0092] FIG. 11A depicts the relative power levels 1100 of example embodiments of the present invention. FIG. 11A is not a scale drawing. This embodiment doubles the pre-existing rate 6/7 capacity by using a TWTA 6.2 dB above a pre-existing TWTA equivalent isotropic radiated power (EIRP) and second TWTA 2 dB below the pre-existing TWTA power. This embodiment uses upper and lower QPSK layers which are non-coherent. A code rate of 6/7 is also used for both layers. In this embodiment, the signal of the legacy

QPSK signal 1102 is used to generate the upper layer 1104 and a new QPSK layer is the lower layer 1110. The CNR of the legacy QPSK signal 1102 is approximately 7 dB. In the present invention, the legacy QPSK signal 1102 is boosted in power by approximately 6.2 dB bringing the new power level to approximately 13.2 dB as the upper layer 1104. The noise floor 1106 of the upper layer is approximately 6.2 dB. The new lower QPSK layer 1110 has a CNR of approximately 5 dB. The total signal and noise of the lower layer is kept at or below the tolerable noise floor 1106 of the upper layer. The power boosted upper layer 1104 of the present invention is also very robust, making it resistant to rain fade. It should be noted that the invention may be extended to multiple layers with mixed modulations, coding and code rates.

[0093] In an alternate embodiment of this backwards compatible application, a code rate of $2/3$ may be used for both the upper and lower layers 1104, 1110. In this case, the CNR of the legacy QPSK signal 1102 (with a code rate of $2/3$) is approximately 5.8 dB. The legacy signal 1102 is boosted by approximately 5.3 dB to approximately 11.1 dB (4.1 dB above the legacy QPSK signal 1102 with a code rate of $2/3$) to form the upper QPSK layer 1104. The new lower QPSK layer 1110 has a CNR of approximately 3.8 dB. The total signal and noise of the lower layer 1110 is kept at or below approximately 5.3 dB, the tolerable noise floor 1106 of the upper QPSK layer. In this case, overall capacity is improved to 1.55 times that of the legacy signal before implementing the layered modulation.

[0094] In a further embodiment of a backwards compatible application of the present invention the code rates between the upper and lower layers 1104, 1110 may be mixed. For example, the legacy QPSK signal 502 may be boosted by approximately 5.3 dB to approximately 12.3 dB with the code rate unchanged at $6/7$ to create the upper QPSK layer 1104. The new lower QPSK layer 1110 may use a code rate of $2/3$ with a CNR of approximately 3.8 dB. In this case, the total capacity relative to the legacy signal 1102 is

approximately 1.78. In addition, the legacy IRDs will suffer no significant performance degradation.

3.2 Non-Backward Compatible Applications

[0095] As previously discussed the present invention may also be used in “non-backward compatible” applications. In such applications, both upper and lower layer signals may take advantage of advanced forward error correction (FEC) coding techniques to lower the overall transmission power required by the system. In a first example embodiment, two QPSK layers 1104, 1110 are used each at a code rate of 2/3. The upper QPSK layer 504 has a CNR of approximately 4.1 dB above its noise floor 1106 and the lower QPSK layer 1110 also has a CNR of approximately 4.1 dB. The total code and noise level of the lower QPSK layer 1110 is approximately 5.5 dB. The total CNR for the upper QPSK signal 1104 is approximately 9.4 dB, merely 2.4 dB above the legacy QPSK signal rate 6/7. The capacity is approximately 1.74 times that of the legacy rate 6/7 signal.

[0096] FIG. 11B depicts the relative power levels of an alternate embodiment wherein both the upper and lower layers 1104, 1110 are below the legacy signal level 1102. The two QPSK layers 1104, 1110 use a code rate of 1/2. In this example, the upper QPSK layer 1104 is approximately 2.0 dB above its noise floor 1106 of approximately 4.1 dB. The lower QPSK layer has a CNR of approximately 2.0 dB. The capacity of this embodiment is approximately 1.31 times that of the legacy rate 6/7 signal.

4. Hardware Environment

[0097] FIG. 12 illustrates an exemplary computer system 1200 that could be used to implement selected modules and/or functions of the present invention. The computer 1202 comprises a processor 1204 and a memory 1206, such as random access memory (RAM). The computer 1202 is operatively coupled to a display 1222, which presents images such as windows to the user on a graphical user interface 1218B. The computer 1202 may be coupled to other devices, such as a keyboard 1214, a mouse device 1216, a printer, etc. Of course, those skilled in the art will recognize that any combination of the above components, or any number of different components, peripherals, and other devices, may be used with the computer 1202.

[0098] Generally, the computer 1202 operates under control of an operating system 1208 stored in the memory 1206, and interfaces with the user to accept inputs and commands and to present results through a graphical user interface (GUI) module 1218A. Although the GUI module 1218A is depicted as a separate module, the instructions performing the GUI functions can be resident or distributed in the operating system 1208, the computer program 1210, or implemented with special purpose memory and processors. The computer 1202 also implements a compiler 1212 which allows an application program 1210 written in a programming language such as COBOL, C++, FORTRAN, or other language to be translated into processor 1204 readable code. After completion, the application 1210 accesses and manipulates data stored in the memory 1206 of the computer 1202 using the relationships and logic that was generated using the compiler 1212. The computer 1202 also optionally comprises an external communication device such as a modem, satellite link, Ethernet card, or other device for communicating with other computers.

[0099] In one embodiment, instructions implementing the operating system 1208, the computer program 1210, and the compiler 1212 are tangibly embodied in a computer-

readable medium, e.g., data storage device 1220, which could include one or more fixed or removable data storage devices, such as a zip drive, floppy disc drive 1224, hard drive, CD-ROM drive, tape drive, etc. Further, the operating system 1208 and the computer program 1210 are comprised of instructions which, when read and executed by the computer 1202, causes the computer 1202 to perform the steps necessary to implement and/or use the present invention. Computer program 1210 and/or operating instructions may also be tangibly embodied in memory 1206 and/or data communications devices 1230, thereby making a computer program product or article of manufacture according to the invention. As such, the terms “article of manufacture,” “program storage device” and “computer program product” as used herein are intended to encompass a computer program accessible from any computer readable device or media.

[0100] Those skilled in the art will recognize many modifications may be made to this configuration without departing from the scope of the present invention. For example, those skilled in the art will recognize that any combination of the above components, or any number of different components, peripherals, and other devices, may be used with the present invention.

5. On-Line OMUX Filter Measurement

[0101] As described above, the OMUX filter outputs the power signal for downlink to receivers 500, 802. To provide a high fidelity signal with layered modulation and/or to simply monitor or perform a routine satellite payload system check, knowledge regarding the conduct and performance of the OMUX 818 (i.e., the OMUX filter transfer function) is useful. FIG. 8B illustrates the various satellite transponder 107 components for receiving and transmitting signals. OMUX 818 can be seen as transferring/filtering/processing the

signal $F_I(f)$ to $F_O(f)$ (i.e., through an OMUX filter transfer function). Accordingly, the filter transfer function may also be referred to as $S_O(f)$ and is provided by:

$$S_O(f) = \frac{F_O(f)}{F_I(f)}.$$

[0102] However, once the downlink signal $F_O(f)$ is received at receivers 500/802, the receivers do not have any independent knowledge of the OMUX filter transfer function. One or more embodiments provide the ability to estimate the function. FIG. 14 illustrates the processing of FIG. 8B (i.e., where the OMUX transfer function modifies the signal) followed by the on-line measurement of the OMUX filter transfer function in accordance with one or more embodiments of the invention.

[0103] During downlink transmission, signal noise may be accumulated. Accordingly, the downlink signal 808 (also referred to as the estimated OMUX output $F_O'(f)$) is received by receiver 902. Similar to the layered modulation described above, the receiver 902 demodulates (and decodes if necessary) the received signal using a demodulator 1402. The demodulator 1402 may have various signal requirements to ensure proper demodulation. For example, the receiver input low pass filter may be required to be sufficiently wide to accommodate the signal. Also, the receiver carrier to noise ratio must be sufficiently large (e.g., by using a large antenna at the broadcast center) so that excess noise can be avoided.

[0104] Once demodulated, the signal is then re-encoded if necessary and re-modulated (i.e., using remodulator 1404). The remodulated signal $F_I'(f)$ provides an estimate of the signal prior to processing by the OMUX 818. The remodulated signal $F_I'(f)$ can be a close estimate of the input signal $F_I(f)$ to OMUX without the knowledge of the IMUX 814 since the effects of the IMUX 814 are generally negligible. The remodulator 1404 actually also provides and account for TWTA AM/AM and AM/PM maps/distortion. Thus, the

demodulation 1402 and remodulation 1404 reconstructs the signal while taking the effects of the IMUX 814 and TWTA 816 into account.

[0105] After processing, the receiver 902 has the estimated OMUX 818 input $F_I'(f)$ from the reconstructed signal and the estimated OMUX 818 output $F_O'(f)$ from the received signal. FIG. 15A illustrates the simulated/estimated signal spectrum $F_I'(f)$ without the OMUX filter 818. In the illustration, the input CNR is 49 dB (noiseless) and the receiver low pass filter bandwidth (LPF BW) is 99 MHz (all-pass). Similar to FIG. 15A, FIG. 15B illustrates the simulated/estimated signal spectrum $F_O'(f)$ with the OMUX filter 818.

[0106] To measure the OMUX 818 filter transfer function, the two signals (of FIG. 15A and 15B) are compared. Accordingly, the estimated OMUX transfer function $S_O'(f)$ may be determined based on:

$$S_O'(f) = \frac{F_O'(f)}{F_I'(f)}$$

[0107] Careful analysis of the signals illustrated in FIGs. 15A and 15B show some slight differences between the signals with and without the OMUX 818.

[0108] The result of the comparison provides the estimated OMUX transfer function. While FIG. 13. illustrates the actual OMUX 818 transfer function, FIG. 16 illustrates the estimated OMUX 818 transfer function in accordance with one or more embodiments of the invention. The graph illustrates the phase/magnitude to frequency in the same form as in FIG. 13. Comparing the graph of FIG. 13 to FIG. 16, within the designed signal range of -12 MHz to 12 MHz, the estimated OMUX 818 transfer function is fairly accurate. However, beyond this range where the signal is generated by a small TWTA nonlinearity, signal noise is significantly increased. To improve the measurement accuracy beyond the range, and to reduce these noise artifacts, additional samples may be processed.

[0109] Once the estimated transfer function has been obtained, it may be used in layered modulation or as part of payload system monitoring. In this regard, based on the estimated transfer function of FIG. 16, it may be presumed that if the OMUX 818 is very wide, significant noise artifacts may be included in the estimated transfer function. Accordingly, the layered modulation cancellation (described above) may not need to be adjusted (such adjustment may be inaccurate due to the noise). However, if the OMUX 818 is narrow (i.e., filters within the -12 MHz to 12 MHz range), the effect of the filter may be applied during layered modulation.

[0110] FIG. 17 is a flow chart illustrating the process for measuring the OMUX transfer function in accordance with one or more embodiments of the invention. At step 1700, the broadcast downlink signal $F_O'(f)$ is received. As described above, such a signal may comprise an estimate OMUX 818 output due to noise during the downlink process.

[0111] At step 1702, the signal $F_O'(f)$ is demodulated and then remodulated at step 1704 to provide an estimated OMUX input signal $F_I'(f)$.

[0112] At step 1706, the received broadcast downlink signal $F_O'(f)$, and the remodulated signal $F_I'(f)$ are compared to estimate the OMUX transfer function of the satellite. The estimated OMUX transfer function may include bandwidth, flatness, and group delay properties that may be used in the layered modulation. Step 1708 is optional and may provide for the utilization of the comparison/estimated transfer function (e.g., in layered modulation signal processing or part of satellite payload system monitoring).

[0113] Step 1700-1708 may all be performed by a receiver 902. Further, when conducting the remodulating at step 1704, it is assumed that the effects of the IMUX 814 are negligible. Further, the remodulating 1704 also includes accounting for the TWTA 816 maps/distortion. The comparison at step 1706 may be provided in accordance with a ratio of the received broadcast downlink signal $F_O'(f)$ to the remodulated signal $F_I'(f)$.

[0114] This concludes the description including the preferred embodiments of the present invention. The foregoing description of the preferred embodiment of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching.

[0115] It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto. The above specification, examples and data provide a complete description of the manufacture and use of the apparatus and method of the invention. Since many embodiments of the invention can be made without departing from the scope of the invention, the invention resides in the claims hereinafter appended.